Design-of-Experiment Based Systematic Tuning of Square Open Loop Resonator

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***Abstract*— Stub-loaded, square open loop resonator (SOLR) is a type of bandpass filter with dual-band response. It is believed that its center frequency values are determined by entire length of open loop resonator's and open stub's lengths, the bandwidth values are determined by coupling between two resonators. However, design of experiments (DOE) method applied in this paper shows that the center frequency values are also affected by interaction between resonator length, stub length, and distance between the two resonators in pair. The DOE also shows that bandwidth values, both upper and lower bands, are not only affected by the distance between resonators but also by the resonator's and stub's lengths. Utilizing slope values of the significant factors, systematic tuning to SOLR can be done. With few steps, small error on frequency responses can be obtained.**

Keywords—stub-loaded resonator, square open loop resonator, bandpass filter, dual-band, design of experiment

I. Introduction

Stub-loader resonator (SLR) type of square open-loop resonator (SOLR) produce dual-band response of bandpass filter (BPF) [1]. SLR-based structures have been applied for various dual-band or multiband BPF designs [2-4] and also integrated dual-band filter/duplexer antenna [5]. The variation of resonator shape or integration of other structure to SLR has enabled many new filter designs with specific characteristics and opened new applications. This shows the significance of SLR in RF and microwave engineering field.

SLR-based SOLR bandpass filter has four main design parameters, i.e. resonator length (L_1), stub length (L_2), gap between a resonator's end (g_2), and distance between resonator pair (g_1). Using analytical model [1] it has been shown that the filter's center frequency values are determined by the resonator length (lower-band, F_1, and higher-band, F_2) and stub length (higher-band, F_2). It is not clear what factors that are significant to affect the values of lower-band bandwidth (B_1) and higher-band bandwidth (B_2), and also the interactions among the design parameters to influence the values of F_1, F_2, B_1, and B_2. The knowledge is very important in order to design the filter accurately and to provide systematic tuning method to achieve the specification.

This paper analyzes SLR-based SOLR significant design parameters (factors) to determine the filter performance metrics (responses: F_1, F_2, B_1, and B_2), sees interactions among factors, obtains slope values that provide direction and value for systematic tuning. Design of experiment (DOE) which uses statistical method is utilized to achieve the goals. The method has been successfully employed in microwave antennas and filters, e.g. [6-8].

II. Initial Design

A. Shape and Dimension

SLR-based SOLR's configuration and its corresponding design parameters are described in Fig. 1. The values of design parameters are tabulated in Table 1. The main design parameters are resonator length (L_1), stub length (L_2), distance between resonator pair (g_1), and gap between a resonator's end (g_2). Other parameters are feedline length (L_P), feedline width (W_p), resonator width (W_1), stub width (W_2), and substrate thickness (h).

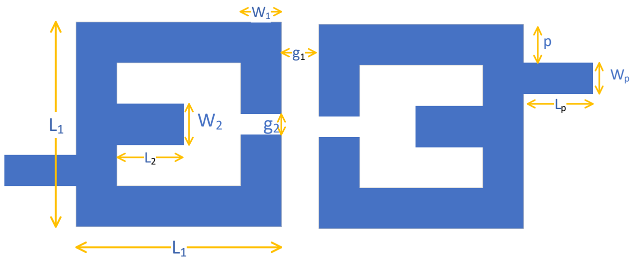

Fig. 1. SLR-based SOLR design and its parameters.

TABLE I. Design Parameters of SOLR

Main Factors	Length (mm)
L_1	7.75
L_2	4.7
g_1	0.6
g_2	0.6

Fixed Parameters	Length (mm)
W_1	0.6
W_2	1.5
L_p	3.7
W_p	0.6
h	0.64
p	0.9

B. Material

The substrate for the filter is Rogers RO3210. This PCB has relative permittivity (ϵ_r) of 10.8, dissipation factor (tanδ) of 0.0027, and thickness (h) of 0.64 mm. Effective dielectric constant for this substrate is 7.22.

C. Simulation Results

SOLR design with chosen substrate and dimension was simulated with CST Microwave Studio. S21 magnitude curve over frequency is shown in Fig. 2.and the performance metrics (responses) is summarized in Table 2. According to formula in [1], F_1 should be 1.99 GHz and F_2 is 2.99 GHz. The discrepancy of F_1 is 203 MHz (9%) and F_2 is 378 MHz (11%). In the following sections, we investigate whether the differences are caused by limitation of the analytical model used or interaction of design parameters that was not considered in [1].

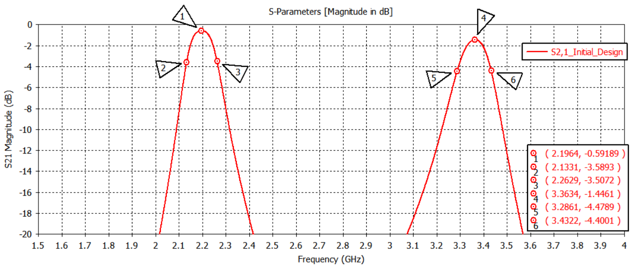

Fig. 2. Simulated S21 magnitude of the initial design.

TABLE II. PERFORMANCE METRIC OF INITIAL DESIGN

Response	Value (GHz)
F_1	2.1964
B_1	0.1309
F_2	3.3634
B_2	0.1477

D. BPF Specification

From the initial BPF design, it intended to produce at filter with specification as listed in Table 3. The goal is challenging in the sense that the correction values are large and the direction of F_1 and F_2 changes are on the contrary.

TABLE III. BPF SPECIFICATION AND NEEDED CORRECTION

Response	Specification (GHz)	Discrepancy (%)	Correction (GHz)
F_1	2.045	7.4%	-0.1514
B_1	0.25	-47.6%	0.1191
F_2	3.5	-3.9%	0.1366
B_2	0.25	-40.9%	0.1023

III. DESIGN OF EXPERIMENT

To avoid trial-and-error tuning, the knowledge of significant factors and their sensitivity (response shift ratio to factor change) is very important. Design of experiment employing statistical method can provide this information and facilitates SOLR filter designers to make systematic tuning to achieve the filter specification.

A. Factors and Responses

In DOE, input variables are called factors and output variables are attributed as responses. This paper uses L_1, L_2, g_1, and g_2 as factors and F_1, F_2, B_1, and B_2 as responses. Each factor is varied $\pm 5\%$ from its nominal value. DOE method used in this paper is two-level, full factorial design. CST Microwave Studio is used to simulate SOLR filter with all combination of factors and each response is recorded.

B. DOE Data

Electromagnetic simulations conducted with CST Microwave Studio to all combinations of factor values are presented in Table 4. The value of "+1" in the factor means 5% above nominal value (see Table 1), "-1" is 5% below nominal value. As an example, "+1" in L_1 corresponds to 8.1375 mm (105% of 7.75 mm) and "-1" relates to 7.3625 mm (95% of 7.75 mm).

TABLE IV. DOE DATA AS RESULTS OF ELECTROMAGNETIC SIMULATIONS

Factor				Response (GHz)			
g_2	g_1	L_2	L_1	F_1	B_1	F_2	B_2
-1	-1	-1	-1	2.293	0.1742	3.5446	0.193
+1	-1	-1	-1	2.2948	0.1749	3.5452	0.1947
-1	+1	-1	-1	2.3008	0.1452	3.5542	0.1692
+1	+1	-1	-1	2.3026	0.1455	3.5548	0.1693
-1	-1	+1	-1	2.2966	0.1746	3.4408	0.1838
+1	-1	+1	-1	2.2984	0.1748	3.442	0.1837
-1	+1	+1	-1	2.305	0.1456	3.46	0.1521
+1	+1	+1	-1	2.3068	0.1465	3.4606	0.1519
-1	-1	-1	+1	2.0416	0.1566	3.2404	0.1842
+1	-1	-1	+1	2.047	0.1584	3.2428	0.1837
-1	+1	-1	+1	2.0524	0.1294	3.2482	0.1628
+1	+1	-1	+1	2.0578	0.1304	3.2506	0.1613
-1	-1	+1	+1	2.0434	0.156	3.1666	0.1709
+1	-1	+1	+1	2.0488	0.1573	3.1684	0.1702
-1	+1	+1	+1	2.0548	0.1295	3.175	0.1463
+1	+1	+1	+1	2.0602	0.1307	3.1768	0.1464

C. Significant Factors and Their Slope Values

DOE data listed in Table 4 are analyzed in Minitab. The significant factors and their slope values are tabulated in Table 5. It is noted here that empty cells mean "non-significant factors." The value in the cell is slope. It is sensitivity of a response to factor change. As an example, the slope of F_1 to L_1 is -0.1245 GHz. It can be interpreted that change of "+1" (+5% of L_1 nominal value) will shift down F_1 as far as 124.5 MHz.

TABLE V. SIGNIFICANT FACTORS DAN SLOPES

Factor	Response (GHz)			
	F_1	B_1	F_2	B_2
g_2	0.0018		0.0007	
g_1	0.0048	-0.0140	0.0056	-0.0128
L_2	0.0015	0.0000	-0.0432	-0.0071
L_1	-0.1245	-0.0083	-0.1458	-0.0045
g_2*g_1				
g_2*L_2				
g_2*L_1	0.0009			
g_1*L_2	0.0002	0.0002	0.0012	-0.0012
g_1*L_1	0.0007	0.0005	-0.0015	0.0013
L_2*L_1	-0.0005		0.0063	
g_2*g_1*L_2				
g_2*g_1*L_1				
g_2*L_2*L_1				
g_1*L_2*L_1			-0.0011	
g_2*g_1*L_2*L_1				

D. Tree Diagram of Significant Factors

The significant factors as listed in Table 5 can be ranked and taken 10% threshold relative to the largest slope value of each factor respectively. This threshold produces simpler, systematic structure as presented in Fig. 3. Relations of responses to significant factors shows that (i) F_1 is not only determined by L_1but also by g_1, (ii) F_2 is mostly influenced by L_1 and L_2 hence it confirms the formula in [1], (iii) B_1 is affected by g_1 and L_1, (iv) B_2 is controlled by g_1, L_2, and L_1, (v) g_2 is not a significant and high impact factor. It is also can be identified that F_1 and F_2 are dominated by L_1. The slope values of B_1 and B_2 are relatively small (around 12 MHz per 5% change of g_1) as indication that the lower and upper-band bandwidth values are rather difficult to be tuned.

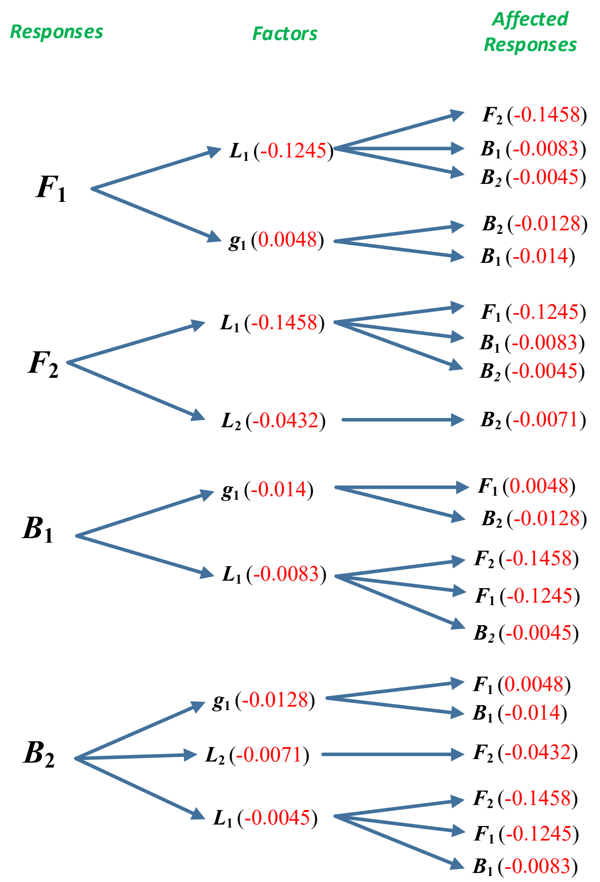

Fig. 3. Tree diagram of significant factors.

If $F_1$is to be increased 124.5 MHz there are two options: (i) reducing $L_1$by 5% from current value, or (ii) increase g_1 by 124.5/4.8 x 5% from current value. A designer must be aware that changing the value of L_1 not only shifts F_1 but also affects F_2, B_1, and B_2. To increase F_1 but to keep F_2 current value can be done by (i) increasing the value of g_1 is the required shift is small or (ii) decreasing L_1 and increase L_2 although it may be difficult since L_1's slope to F_2 is more than three times L_2's.

IV. Evaluation of Tuning Accuracy

The slope values are used to tune the filter's response. Comparison of response shift predicted from slope and actual change resulted from CST Microwave Studio simulation can be used to evaluate the effectiveness and accuracy of systematic tuning employing DOE method.

A. Single-factor Tuning

First factor to be tuned is L_1. In this case, L_1 is changed to be 7.8442 mm or +1.2% from its nominal value. The predicted shift in F_1 is $\frac{1.2\%}{5\%} \times (-0.1245\text{ GHz}) = -30$ MHz and the new value of $F_1 = 2.166$ GHz. Electromagnetic simulation produces $F_1 = 2.1544$ GHz hence the prediction error is 0.5%.

Table 6 presents prediction error of single factor tuning involving change in L_1, L_2, g_1, g_2, and combination of change L_1, L_2, and g_1. It can be identified that F_1 prediction errors are no more than 0.8%, F_2 are no more than 0.3%, B_2 are around 11%, and B_1 are about 13%. Three factors are varied less than 5% from nominal and one factor differs more than 5%. Table 6 shows that the error statistics are not influenced by the percentage of change from nominal value, provided that the deflection is not very far from 5%.

TABLE VI. Prediction Errors of Single and Multi-Factor Tuning

Response	Single-factor				Multi-factor
	$\Delta L_1 = 1.2\%$	$\Delta L_2 = -8.7\%$	$\Delta g_1 = 2.5\%$	$\Delta g_2 = 2.5\%$	$\Delta L_1, \Delta L_2, \Delta g_1$
F_1	0.5%	0.4%	0.8%	0.3%	1.0%
B_1	-13.2%	-11.5%	-13.2%	-11.8%	-13.5%
F_2	0.3%	0.3%	0.3%	0.2%	0.4%
B_2	-10.9%	-10.9%	-11.6%	-10.0%	-12.6%

B. Multifactor Tuning

The last column in Table 6 presents prediction error of filter's response when L_1, L_2, and g_1 are tuned simultaneously. The variations of the factors are the same with the single-factor. The error values are slightly higher than single-factor's errors. The additional errors come from interaction among varied factors with slope values listed in Table 5, see entries at the first column in the table that contain *. Tuning more than one factor simultaneously does not merely produce superposition of responses from single-factor.

V. Systematic Tuning

Tree diagram in Fig. 3 give clear direction on steps to systematic tuning. Table 5 can be utilized in spreadsheet to calculate predicted response values as chosen factor's modified. Consider the correction needed as listed in Table 3, slope values and dependencies among significant factors, the following steps are taken. Firstly, discrepancy in F_1 is handled with L_1. Needed correction to F_2 is tackled by L_2. Then discrepancies on B_1 and B_2 are corrected with g_1 modification. Adjustment to L_1, L_2, and g_1 are needed to produce response values closest to the filter specification.

To shift F_1 to be 2.045 GHz, L_1 is adjusted to 6.1% (-0.1514 GHz / -0.1245 GHz x 5%). Unfortunately, this adjustment shifts F_2 to 3.186 GHz and should be increased 314 MHz; L_2 needs to be reduced 36.3% (0.314 GHz / -0.0432 GHz x 5%). As listed in Table 5, modifications of L_1 and L_2 values do not only affect F_1 and F_2 independently but ΔL_2 also change F_1, B_1, and B_2; $L_1 * L_2$ contributes frequency shift to F_1 and F_2. Now the response values are $F_1 = 2.039$ GHz, $F_2 = 3.444$ GHz, $B_1 = 0.121$ GHz, and $B_2 = 0.194$ GHz. Correction to B_1 is handled by g_1 and taking similar steps $\Delta g_1 = -46.1\%$. The adjustments to three factors produce $F_1 = 2.000$ GHz, $F_2 = 3.400$ GHz, $B_1 = 0.258$ GHz, and $B_2 = 0.218$ GHz. These results suggest us to do fine tuning to L_1, L_2, and g_1. The fine adjustment made is listed in column "Tuning 1" at Table 7. SOLR filter with this design-parameter set is simulated with CST Microwave Studio and the results are presented in Table 8.

The electromagnetic simulation results of "Tuning 1" agree very well with DOE prediction except for B_2. The lower-band bandwidth is 10.5% wider than its specification and higher-band bandwidth is significantly larger than its specification (51.6%). To improve the filter performance, second tuning is done, see "Tuning 2" in Table 7 for factor values and Table 8 for tuning performance. The error and discrepancy of B_2 can be reduced at the expense of B_1. The errors and discrepancies of F_1 and F_2 can be kept small.

TABLE VII. CHANGE OF FILTER DIMENSION IN TUNING

Factor	Tuning 1		Tuning 2	
	Length (mm)	***Change***	***Length (mm)***	***Change***
L_1	8.0778	4.2%	8.1321	4.9%
L_2	2.9229	-37.8%	2.8054	-40.3%
g_1	0.3148	-47.5%	0.4498	4.9%
g_2	0.6000	0.0%	0.6000	0.0%

TABLE VIII. PERFORMANCE OF TUNING RESULTS

Response	Tuning 1		Tuning 2	
	Prediction Error	***Discrepancy from Specification***	***Prediction Error***	***Discrepancy from Specification***
F_1	-0.6%	0.7%	-0.4%	0.5%
B_1	-3.2%	10.5%	-2.3%	-18.8%
F_2	-0.4%	0.6%	-0.9%	0.9%
B_2	-40.9%	51.6%	-33.0%	25.5%

Comparison of S21 curves among nominal (initial design), Tuning 1, and Tuning 2 is presented in Fig. 4. Transmission zeros are also shown in the figure. The first two zeros of Tuning 1 and Tuning 2 are collocated. The first passband characteristic of Tuning 1 and Tuning 2 differs by pole separation; Tuning 1's poles are separated further hence producing a shallow valley in the passband. The nominal's two first poles are collocated or separated by only a small frequency distance therefore it has narrower bandwidth.

Tuning 1's and Tuning 2's second and third transmission zeros are separated quite far hence their second bandwidth are very wide. The inclusion of additional zero may improve the performance. On the contrary, Nominal's second and third zeros are in closer frequency distance therefore its higher-band is narrower. The absence of valley in second passband indicates that there is only one pole in it.

Poles and zeros determine filter characteristics. To improve filter performance further, a study on relation between factor and pole/zero locations should be done. Design-of-experiment may be employed to achieve this goal.

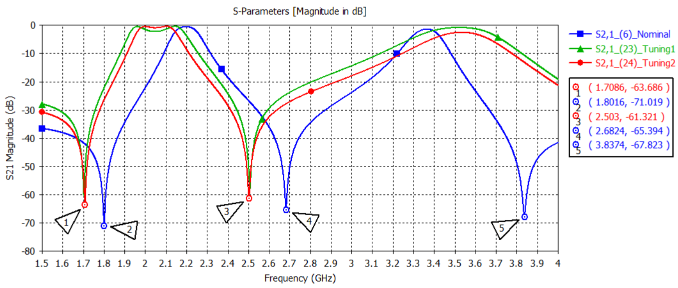

Fig. 4. Comparison of S21 magnitude of initial design (Nominal), Tuning 1, and Tuning 2.

VI. CONCLUSION

DOE analysis reveals that lower-band center frequency is not only determined by the length of resonator but also by the gap between resonators in pair. The bandwidth values are affected mostly by the gap between resonators in pair. The slope resulted from DOE can be used to accurately predict center frequencies ($\leq 1\%$) and bandwidths ($\leq 13.5\%$) caused by design-parameter adjustments. It has been shown that tuning process to the SOLR bandpass filter can be conducted systematically. The filter produced by DOE-based tuning has much closer to specification than the initial design.

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